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(54) **ROBOTS, ROBOTIC SYSTEMS, AND RELATED METHODS**

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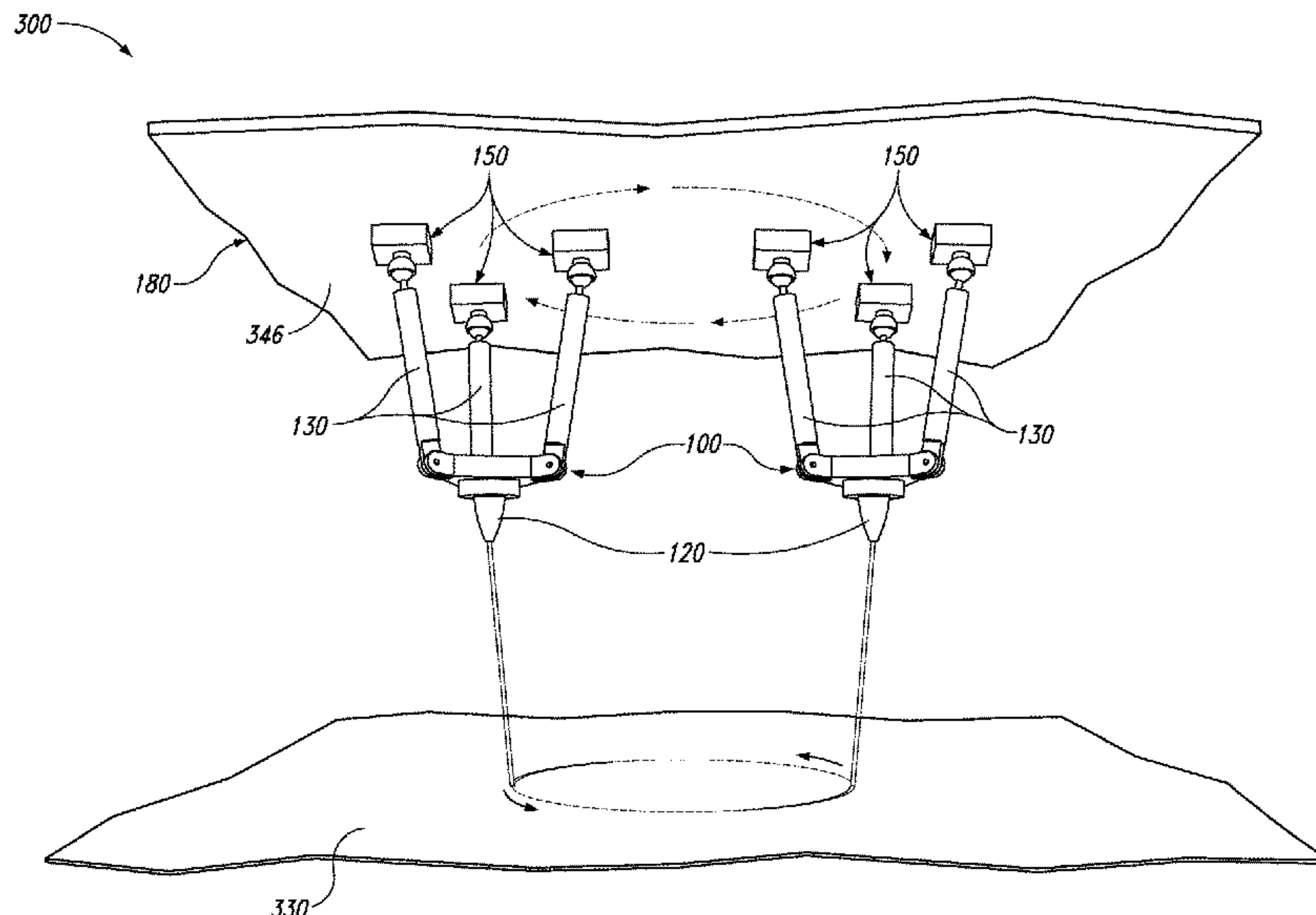
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(57) **ABSTRACT**

Robots for moving relative to a surface, robotic systems including the same, and associated methods are disclosed. A robot includes a body, at least two legs, and at least two feet. Each leg has a proximal end region operatively coupled to the body at a respective body joint with one rotational degree of freedom and a distal end region operatively coupled to a respective foot at a respective foot joint comprising two rotational degrees of freedom. Each foot is configured to be translated relative to the surface with two degrees of translational freedom. Robotic systems include one or more robots and a surface along which the one or more robots are positioned to move. Methods of operating robots and of operating robotic systems include translating at least one foot of a robot to operatively move the body of the robot with six degrees of freedom.

20 Claims, 8 Drawing Sheets



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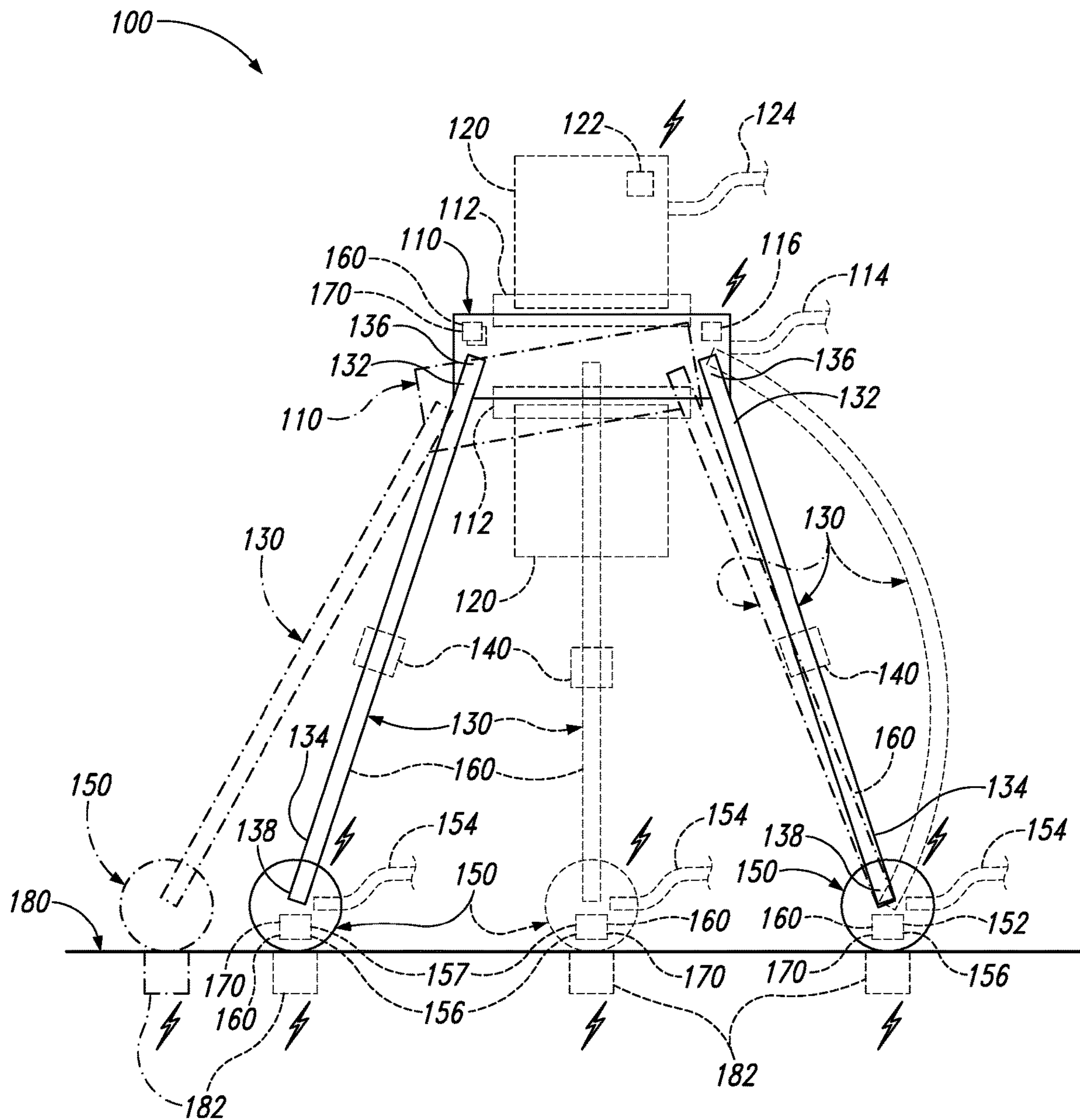


Fig. 1

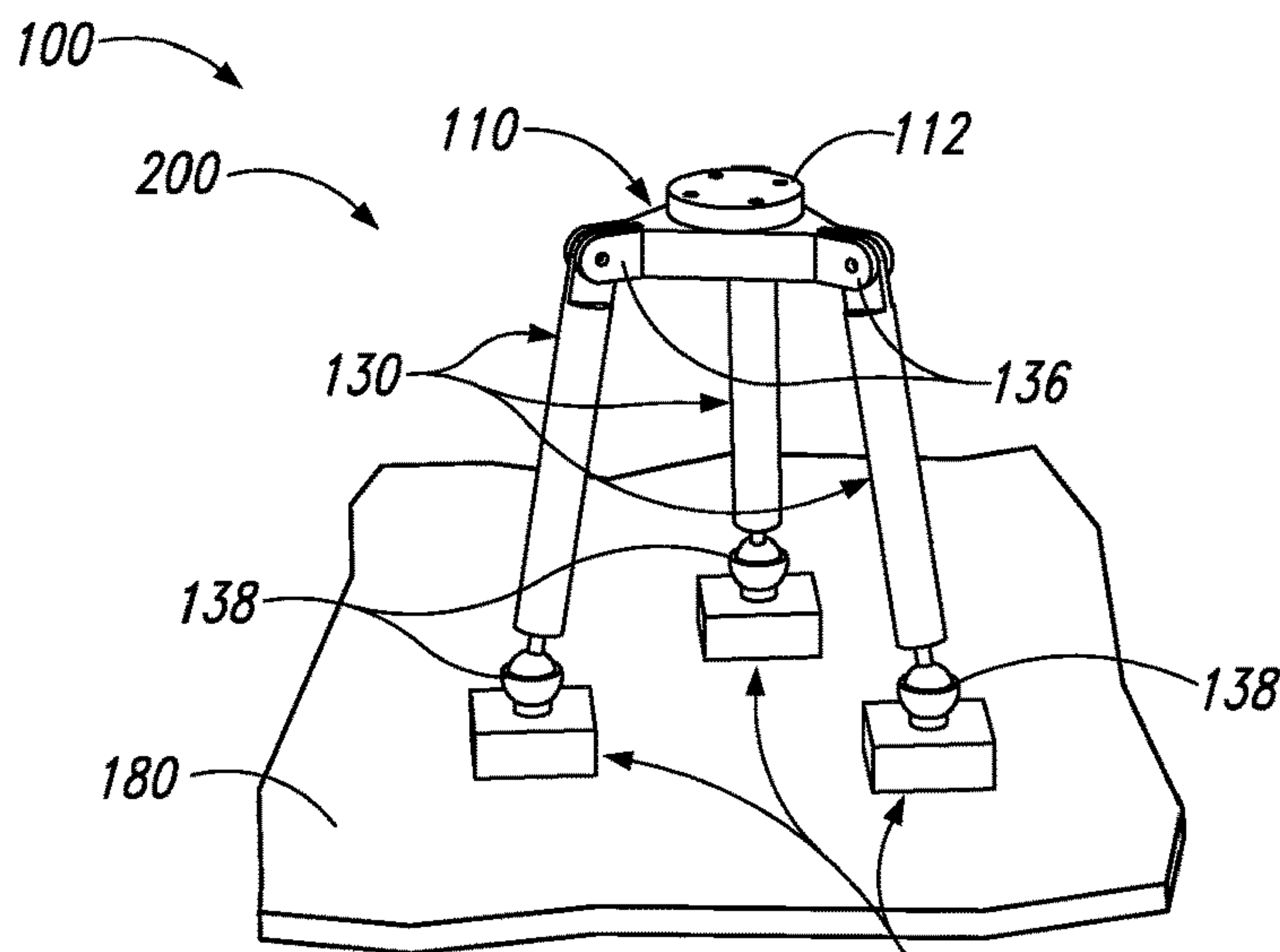


Fig. 2

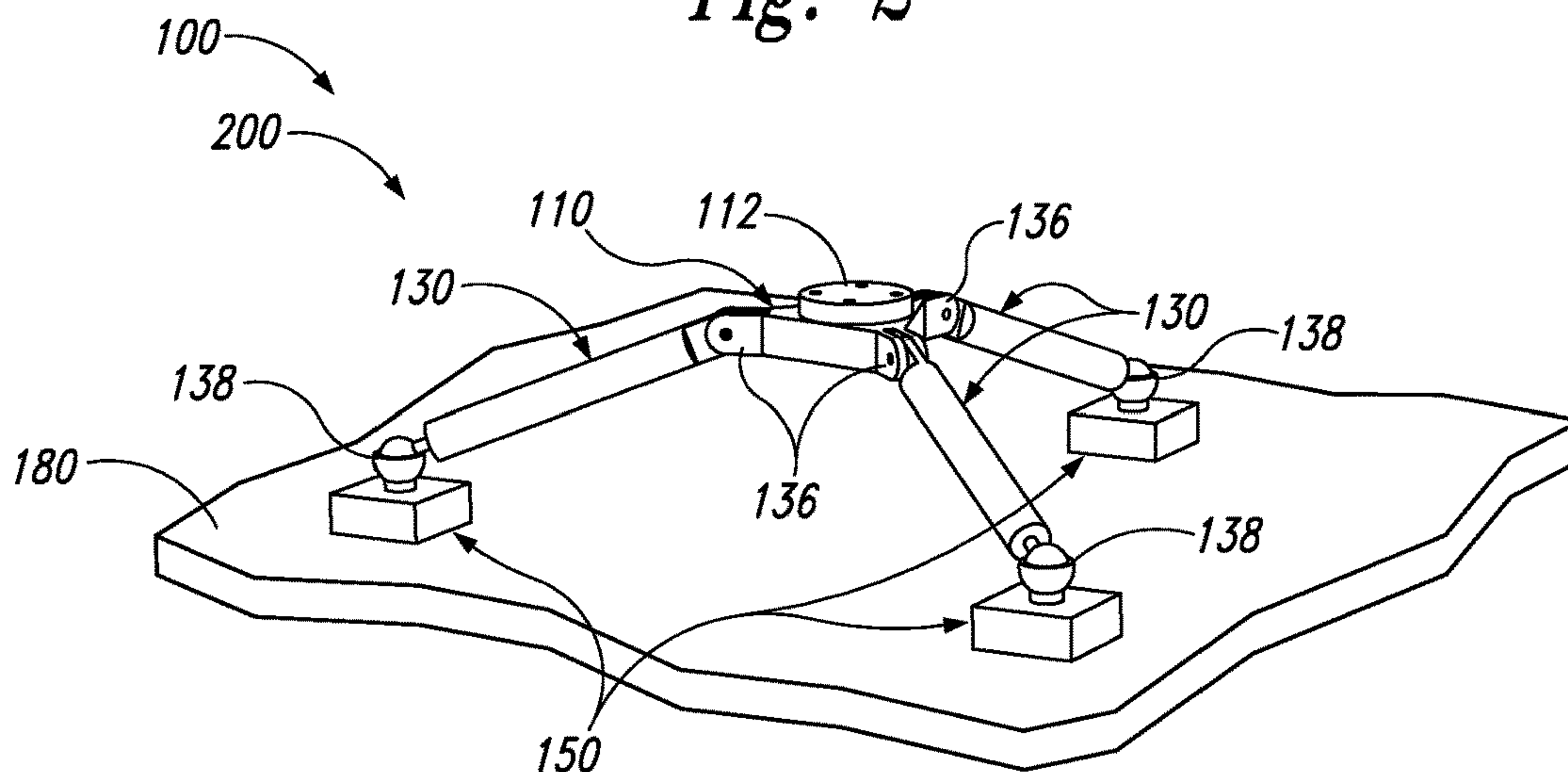


Fig. 3

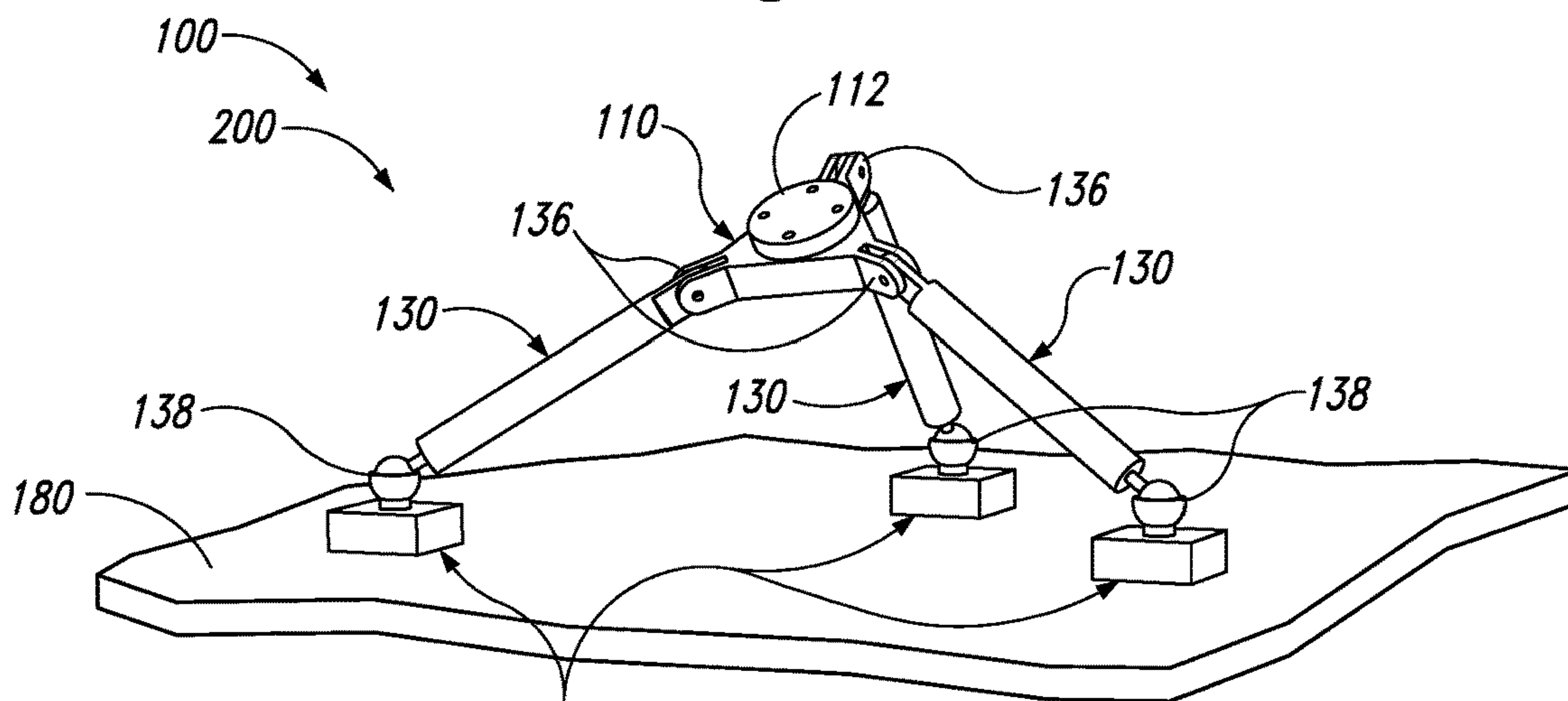


Fig. 4

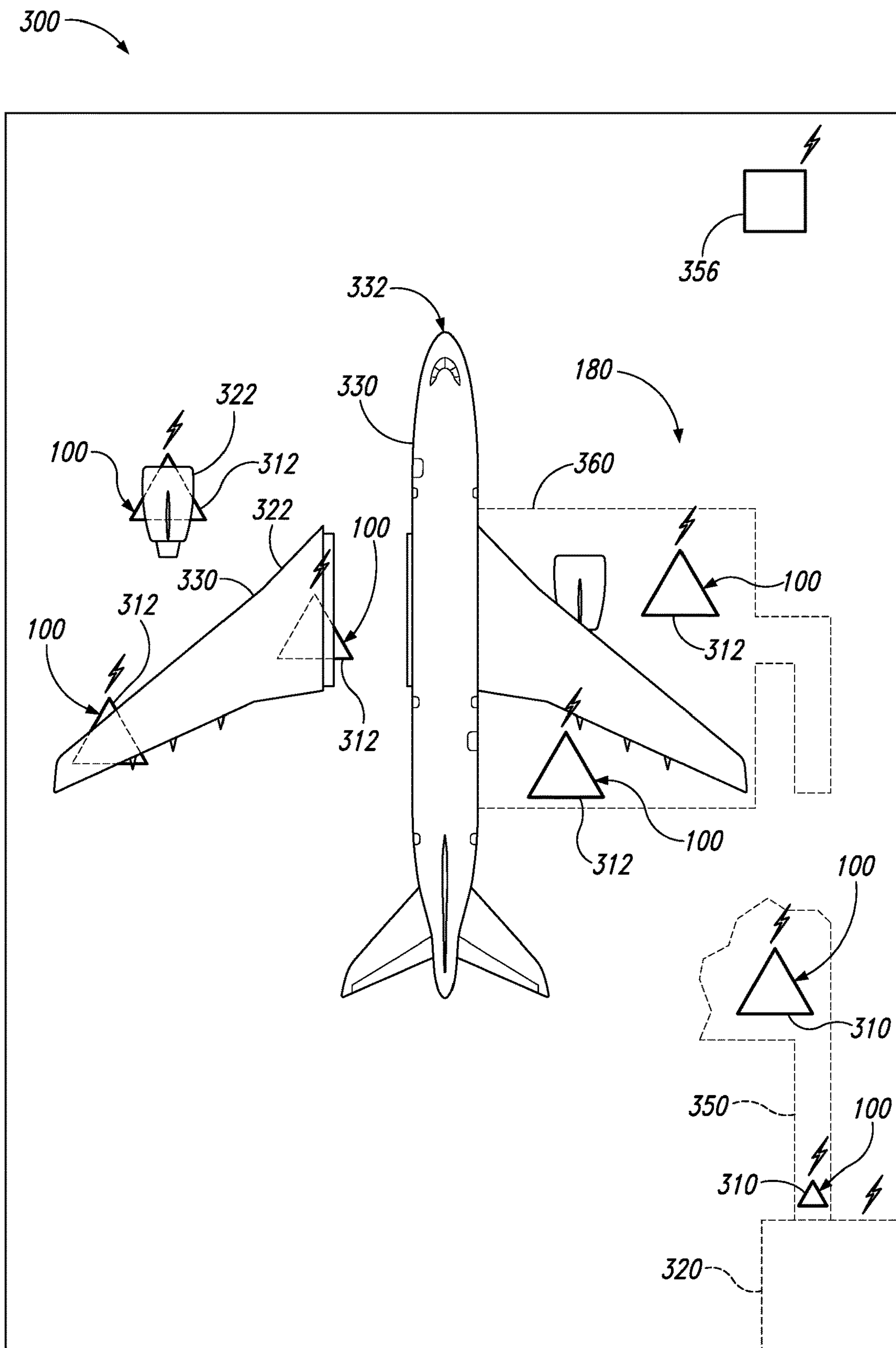


Fig. 5

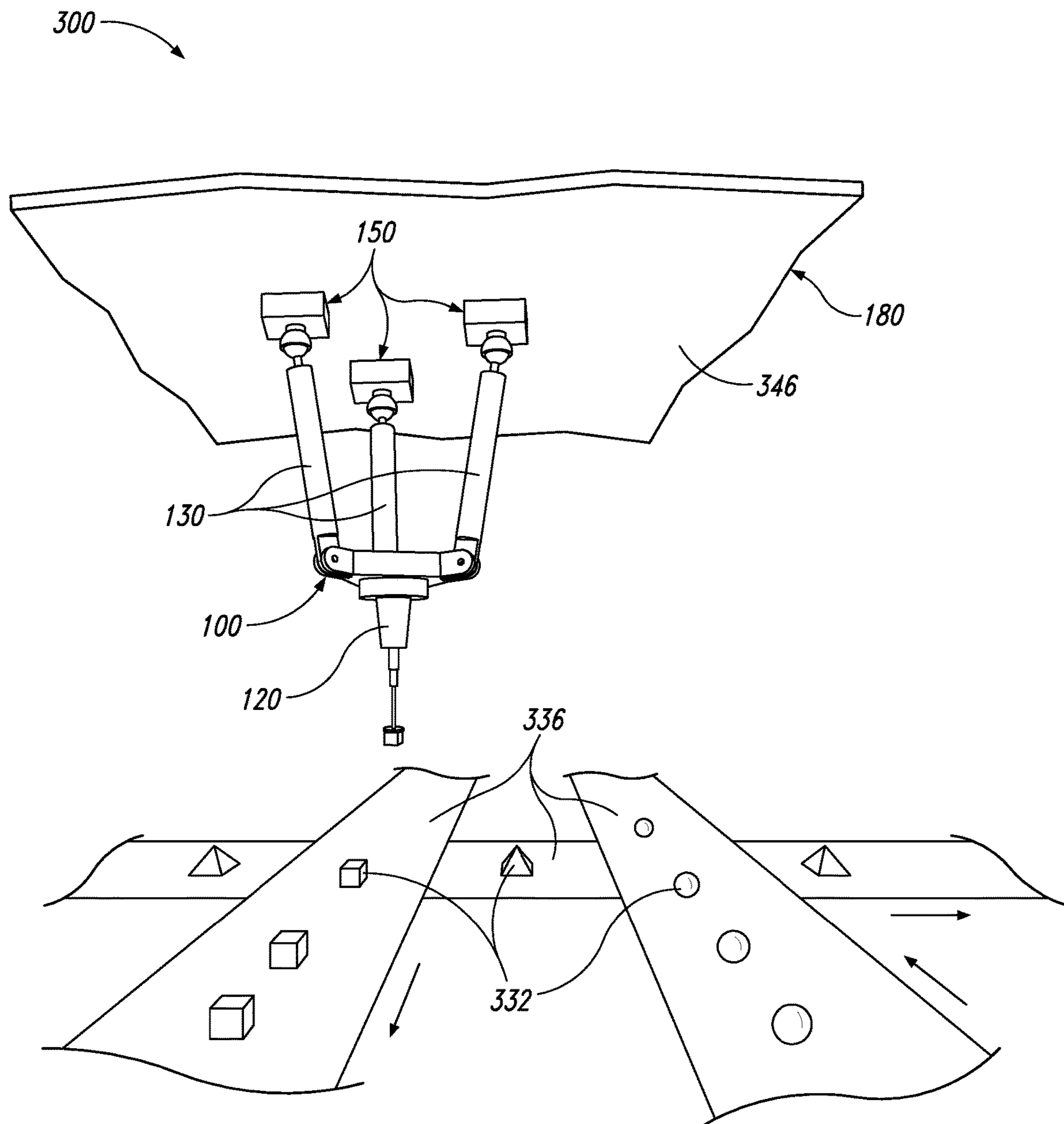


Fig. 7

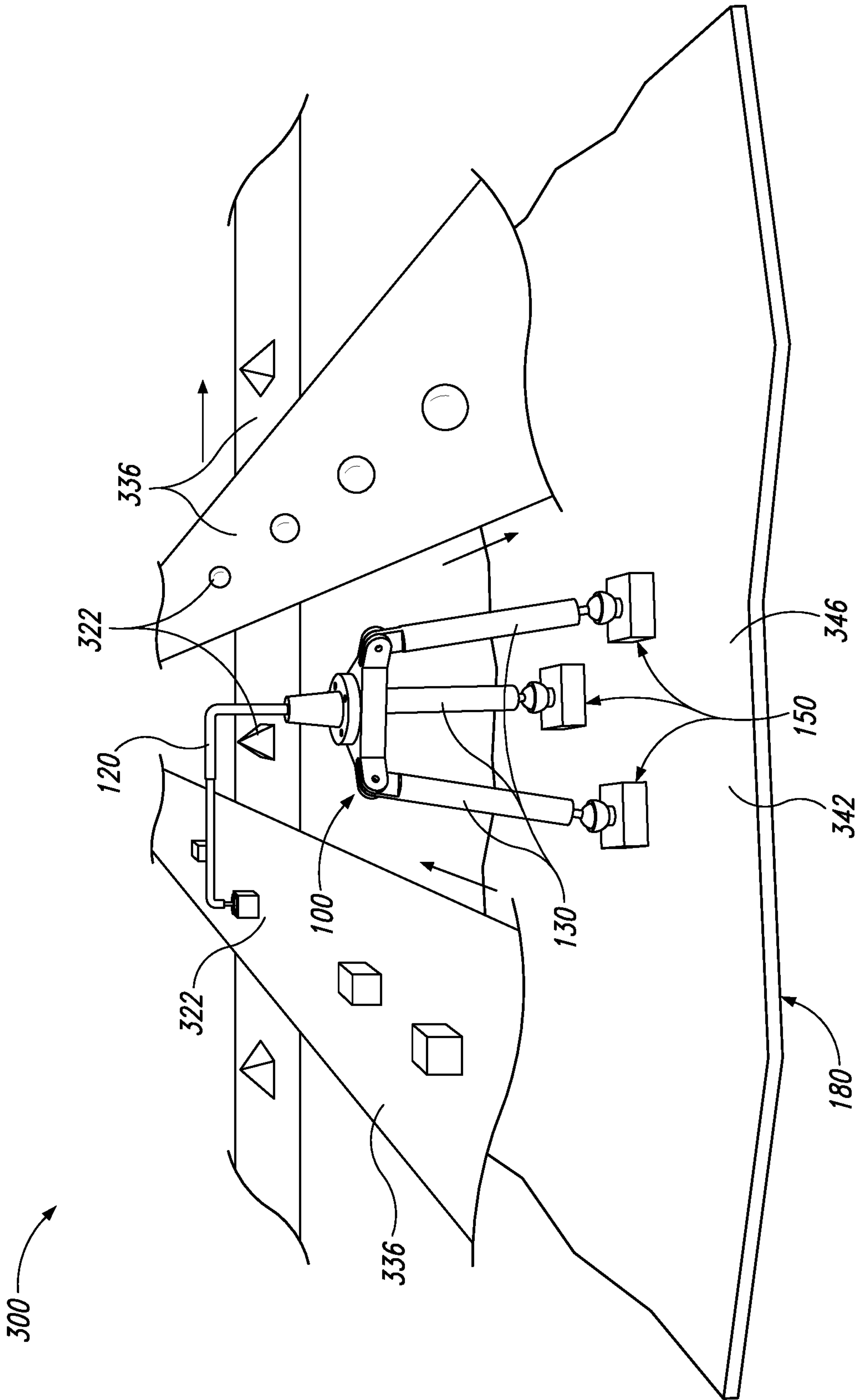


Fig. 8

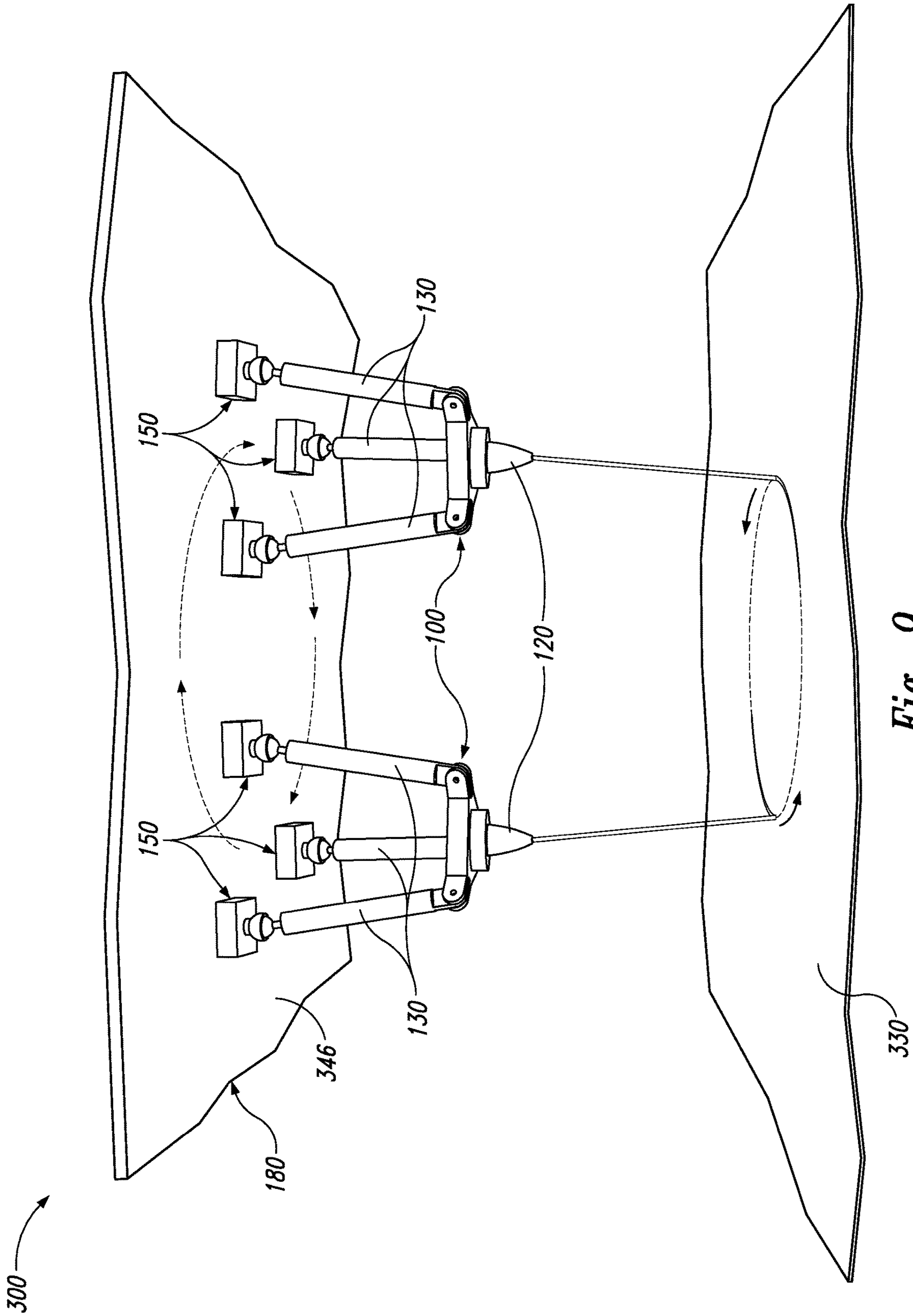


Fig. 9

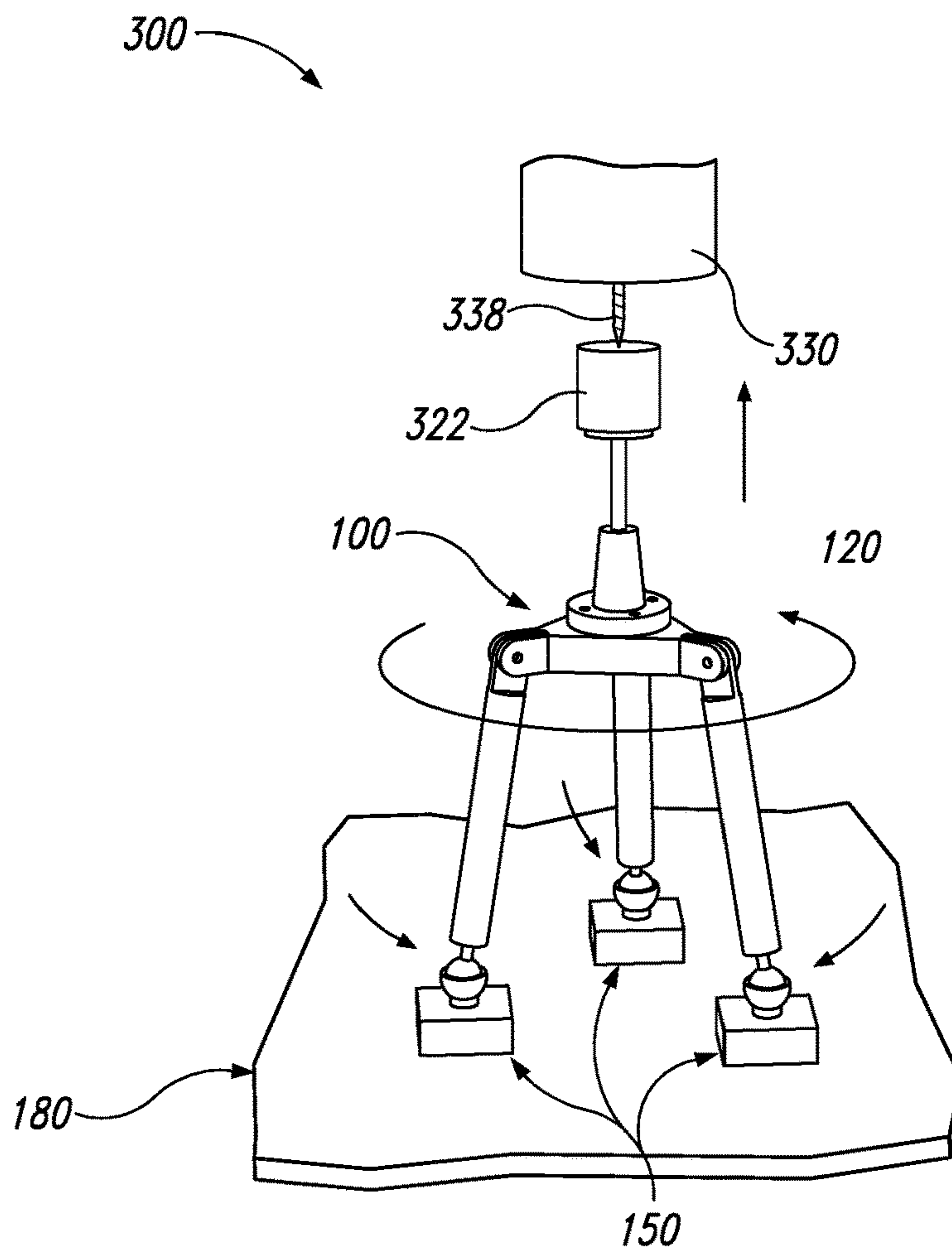


Fig. 10

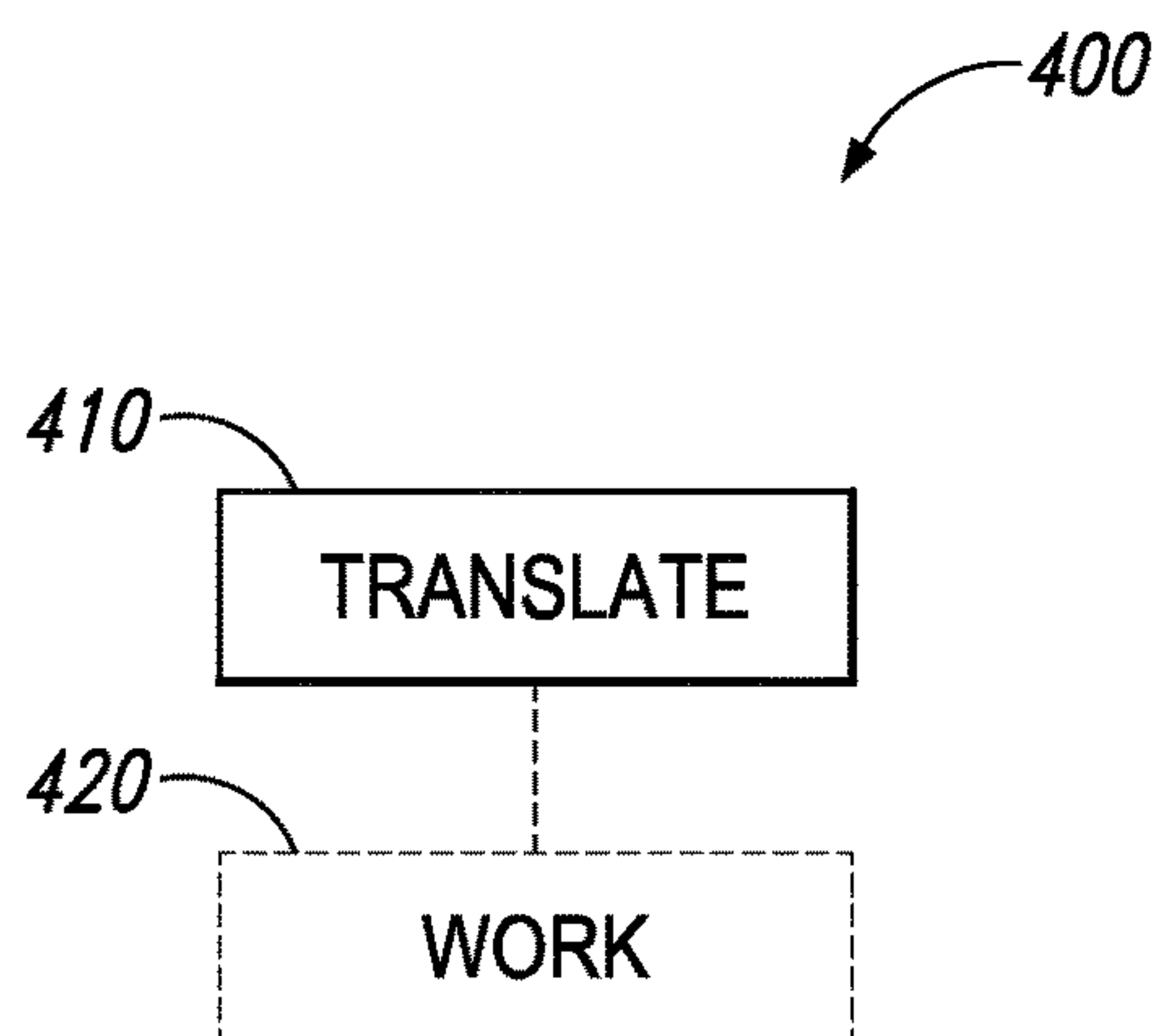


Fig. 11

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ROBOTS, ROBOTIC SYSTEMS, AND
RELATED METHODS

RELATED APPLICATION

This application is a divisional of and claims priority under 35 U.S.C. § 119 to U.S. patent application Ser. No. 15/077,199, which is entitled "ROBOTS, ROBOTIC SYSTEMS, AND RELATED METHODS," which was filed on Mar. 22, 2016, which issued as U.S. Pat. No. 10,345,311 on Jun. 11, 2019, and the disclosure of which is hereby incorporated by reference.

FIELD

The present disclosure relates to robots, robotic systems, and related methods.

BACKGROUND

Modern automated manufacturing facilities commonly utilize kinematic robots to transport, manipulate, and/or assemble work pieces and/or components thereof. Such a robot may be characterized by a number of degrees of freedom (DOF) through which a component of the robot may be moved. For example, a 6 degree of freedom (6 DOF) robot may be capable of moving an end effector mounted on the robot through three translational degrees of freedom (e.g., X, Y, and Z) as well as through three rotational degrees of freedom (e.g., roll, pitch, and yaw). In addition, a robot may be characterized by a work envelope that describes a set of all locations and orientations accessible by the robot. It is generally desirable that a kinematic robot be capable of achieving full 6 DOF motion over a large work envelope while limiting the total size and/or footprint of the robot.

Serial robots generally include a plurality of independently controllable link elements connected in series. While serial robots may allow for motion with up to 6 DOF as well as a large work envelope, their speed and precision are limited. In particular, as a consequence of mounting the link elements in series, the errors of the individual links are compounded, requiring large link elements with extremely fine calibration to achieve end effector accuracy. Consequently, the large mass of the link elements limits the speed with which the serial robot may be manipulated.

Alternatively, parallel robots generally include a plurality of independently controllable link elements connected in parallel, such that the errors of each link element are averaged rather than compounded. However, current designs for parallel robots generally require a large footprint relative to their work envelope and/or achieve full 6 DOF motion only when they include heavy wrist elements added in series with the parallel link elements.

SUMMARY

Parallel kinematic robots for moving relative to a surface, robotic systems including the same, and associated methods are disclosed.

A robot includes a body, at least two legs, and at least two feet. Each leg of the at least two legs has a proximal end region and a distal end region, wherein the proximal end region of each leg is operatively coupled to the body at a respective body joint with one rotational degree of freedom. Each foot of the at least two feet is operatively coupled to the distal end region of a respective leg of the at least two legs at a respective foot joint comprising two rotational degrees

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of freedom. Each foot is configured to be selectively, independently, and motively translated relative to the surface with two degrees of translational freedom. A method of operating a robot includes selectively, independently, and motively translating at least one foot of the at least two feet of the robot to operatively move the body of the robot with six degrees of freedom.

A robotic system includes one or more robots and a surface along which the one or more robots are positioned to move. A method of operating a robotic system includes selectively, independently, and motively translating at least one foot of the one or more robots to operatively move the respective bodies with six degrees of freedom.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration representing robots according to the present disclosure.

FIG. 2 is a perspective view of an example robot according to the present disclosure.

FIG. 3 is another perspective view of the example robot of FIG. 2.

FIG. 4 is another perspective view of the example robot of FIG. 2.

FIG. 5 is a schematic illustration representing robotic systems according to the present disclosure.

FIG. 6 is another schematic illustration representing robotic systems according to the present disclosure.

FIG. 7 is a schematic illustration representing a robotic system according to the present disclosure.

FIG. 8 is a schematic illustration representing a robotic system according to the present disclosure.

FIG. 9 is a schematic illustration representing a robotic system according to the present disclosure.

FIG. 10 is a schematic illustration representing a robotic system according to the present disclosure.

FIG. 11 is a flowchart schematically representing methods of operating robots and robotic systems according to the present disclosure.

DESCRIPTION

Parallel kinematic robots for moving relative to a surface, robotic systems including the same, and associated methods are disclosed. Generally, in the figures, elements that are likely to be included in a given example are illustrated in solid lines, while elements that are optional to a given example are illustrated in broken lines. However, elements that are illustrated in solid lines are not essential to all examples of the present disclosure, and an element shown in solid lines may be omitted from a particular example without departing from the scope of the present disclosure.

As schematically illustrated in FIG. 1, a robot 100 for moving relative to a surface 180 includes a body 110, at least two legs 130, and at least two feet 150. Each leg 130 has a proximal end region 132 and a distal end region 134, wherein the proximal end region of the leg is operatively coupled to body 110 at a respective body joint 136 with one rotational degree of freedom. Each foot 150 is operatively coupled to distal end region 134 of a respective leg 130 at a respective foot joint 138 comprising two rotational degrees of freedom. Each foot 150 is configured to be selectively, independently, and motively translated relative to surface 180 with two degrees of translational freedom. In this way, robot 100 may be configured to bring body 110 to a predetermined position and/or rotational orientation with six degrees of freedom by selectively positioning each foot 150

with respect to each other foot **150** and with respect to surface **180**. Stated differently, robot **100** may be configured such that a location and/or positional orientation of body **110** may be determined based on relative positions of the feet **150** on surface **180**.

As used herein, the terms “selective” and “selectively,” when modifying an action, movement, configuration, or other activity of one or more components or characteristics of an apparatus, mean that the specific action, movement, configuration, or other activity is a direct or indirect result of an input configured to manipulate an aspect of, or one or more components of, the apparatus.

Body **110** may be configured to be operatively coupled to an end effector **120**. Specifically, body **110** may include one or more coupling structures **112** configured to couple an end effector **120** to body **110**. For example, coupling structure **112** may include a mechanical linkage such as a bolt platter configured to receive one or more bolts; however, other examples of coupling structure **112** are within the scope of the present disclosure, and any suitable coupling structure **112** may be utilized.

Body **110** may be configured to be operatively coupled to end effector **120** in any suitable orientation. For example, body **110** may include a first side **111** that generally faces the legs **130** and a second side **113** that generally faces away from the legs **130**, and end effector **120** may be coupled to the body **110** on the first side **111**. In such a configuration, end effector **120** may be described as being positioned between, or generally between, the legs **130**. Additionally or alternatively, body **110** may be configured to be operatively coupled to end effector **120** with end effector **120** coupled to the body **110** on the second side **113**, such that the end effector **120** may be described as being positioned opposite, or generally opposite, the legs **130** relative to the body **110**.

End effector **120** may be any suitable tool for contacting, positioning, manipulating, and/or altering a work piece. For example, end effector **120** may include a welding tool, a drilling tool, a cutting tool, a material removal tool, a fiber placement tool, a gripping tool, a force-torque sensor, a tool changer, and/or a lifting tool. End effector **120** may include an end effector controller **122** configured to selectively translate, manipulate, and/or otherwise control end effector **120** to accomplish a task.

As used herein, a “controller” may be any suitable device or devices that are configured to perform the functions of the controller discussed herein. For example, the controller may include one or more of an electronic controller, a dedicated controller, a special-purpose controller, a personal computer, a special-purpose computer, a display device, a logic device, a memory device, and/or a memory device having non-transitory computer readable media suitable for storing computer-executable instructions for implementing aspects of systems and/or methods according to the present disclosure.

Each body joint **136** may define a single rotational degree of freedom between body **110** and leg **130**. For example, each body joint **136** may consist of a revolute joint such as a single-axis hinge. Body joint **136** may allow for any suitable range of rotational motion of leg **130** with respect to body **110**. For example, body joint **136** may be configured to allow leg **130** to rotate with respect to body **110** through an angular range that is at least 10 degrees, at least 30 degrees, at least 45 degrees, at least 60 degrees, at least 90 degrees, at least 120 degrees, at least 180 degrees, at least 225 degrees, at least 270 degrees, less than 270 degrees, less than 230 degrees, less than 180 degrees, less than 160 degrees, less than 100 degrees, less than 75 degrees, less than 50

degrees, less than 40 degrees, and/or less than 20 degrees. In some examples, body joints **136** may be evenly spaced around a periphery of body **110**. In other examples, body joints **136** may be unevenly spaced around a periphery of body **110**.

Each leg **130** may include, or be, an elongate leg. For example, leg **130** may be characterized by a leg width and a leg length that is substantially larger than the leg width. Each leg **130** may have the same length, or at least substantially the same length. Each leg **130** may have a fixed length or may be configured to be selectively increased and/or decreased in length. For example, leg **130** may be a telescoping leg **130**, and/or may include an extension structure **140** configured to selectively vary a length of leg **130**.

Each leg **130** may be rigid, or at least substantially rigid. For example, leg **130** may be configured such that it remains at least substantially unbent under typical operating conditions. Each leg **130** may be at least substantially linear. Alternatively, at least one leg **130** may be non-linear. For example, and as schematically and optionally illustrated in FIG. 1, leg **130** may have a leg shape that includes an arcuate curve and/or a preformed angle. Such a configuration may be beneficial, for example, in an example in which robot **100** is straddling or otherwise operating proximate to a fixed object, such as a work piece and/or a surface supporting a work piece, such that legs **130** may be moved in close proximity to the fixed object without colliding with the fixed object. Additionally or alternatively, such a configuration may facilitate manipulation of a work piece by end effector **120** in an example in which the end effector **120** is coupled to the first side **111** of body **110** such that the work piece and the end effector **120** are positioned generally between legs **130**.

Robot **100** may include at least three legs **130**, and may include at least three feet **150**. For example, and as schematically illustrated in dashed lines in FIG. 1 and in FIGS. 2-4, the at least two legs **130** may consist of three legs **130**, and the at least two feet **150** may consist of three feet **150**. That is, a robot **100** may include exactly three legs **130** and exactly three feet **150**.

As discussed, each foot joint **138** includes at least two rotational degrees of freedom, which may permit a rotation of leg **130** with respect to foot **150** with a corresponding at least two rotational degrees of freedom. For example, foot joint **138** may be configured to permit a rotation of leg **130** with respect to foot **150** about a roll axis that is substantially parallel to a projection of leg **130** onto surface **180**, about a pitch axis that is substantially perpendicular to the roll axis and substantially parallel to surface **180**, and/or about a yaw axis that is substantially perpendicular to surface **180**. However, this is not required, and it is within the scope of the present disclosure that the at least two rotational degrees of freedom correspond to any appropriate non-parallel rotational axes.

Foot joint **138** may include a spherical joint, a ball joint, a ball-and-socket joint, and/or a universal joint. For example, foot joint **138** may include a spherical joint, a ball joint, and/or a ball-and-socket joint that defines exactly three rotational degrees of freedom.

As discussed, each foot **150** is configured to be selectively, independently, and motively translated relative to surface **180** with two degrees of translational freedom. Foot **150** may include a surface engagement structure **152** configured to contact or otherwise engage surface **180**. For example, foot **150** and/or surface engagement structure **152** may include a planar motor, such as a Sawyer motor, and foot **150** may include a forcer configured to translate foot

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150 relative to surface **180**. Additionally or alternatively, foot **150** and/or surface engagement structure **152** may include one or more wheels, such as spherical wheels and/or motorized wheels. Additionally or alternatively, foot **150** may include an automated guided vehicle (AGV).

Foot **150** and/or surface engagement structure **152** may include an air bearing configured to provide a cushion of air between each foot **150** and surface **180** to minimize a friction force between foot **150** and surface **180**. Additionally or alternatively, surface **180** may include a foot engagement structure **182** configured to contact or otherwise engage with foot **150**, and surface **180** may include an air bearing configured to provide a cushion of air between foot **150** and surface **180**.

Each foot **150** may be configured to be selectively and releasably fixed to surface **180** at a respective location. For example, in an example in which foot **150** and/or surface **180** includes an air bearing configured to provide a cushion of air between foot **150** and surface **180**, the cushion of air may be selectively removed, and/or a binding force such as a magnetic force may be selectively applied to fix foot **150** in place relative to surface **180**. Such a functionality may be desirable, for example, to maintain body **110** in a fixed, or at least substantially fixed, location and/or rotational orientation while end effector **120** performs an operation or receives a load.

As also schematically represented in dashed lines in FIG. **1**, robot **100** may include one or more sensors **160** operatively coupled to one or more of body **110**, leg **130**, and foot **150**. Sensor **160** may be configured to detect one or more of position in three-dimensional space, orientation in three-dimensional space, and acceleration.

Robot **100** additionally may include one or more robot controllers **170** configured to selectively, independently, and motively translate each foot **150** relative to surface **180**. As schematically illustrated in FIG. **1**, a robot controller **170** may be positioned in any suitable location on robot **100**, such as at the body **110** and/or at a foot **150**. Robot controller **170** may be communicatively coupled to the sensors **160**, such as via a wireless protocol, as schematically represented by lightning bolts in FIG. **1**, and/or via a wired communication protocol. In such an example, robot controller **170** may be configured to selectively, independently, and motively translate each foot **150** relative to surface **180** based at least in part on data received from the sensors **160**.

Additionally or alternatively, body **110** may include a body tether **114** that may be configured to provide power and/or commands to body **110**, and hence may operate in place of and/or in conjunction with robot controller **170**. Similarly, foot **150** may include a foot tether **154** that may be configured to provide power and/or commands to foot **150**, and hence may operate in place of and/or in conjunction with robot controller **170**.

Additionally or alternatively, body **110** may include a body battery **116**, and/or foot **150** may include a foot battery **156**, such that body battery **116** and/or foot battery **156** may be configured to provide electrical power to any suitable component of robot **100**, such as body **110**, end effector **120**, foot **150**, sensor **160**, and/or robot controller **170**.

As an example, in operation, robot **100** may be configured to bring end effector **120** to a predetermined position and/or rotational orientation, wherein the position and/or rotational orientation of end effector **120** may be uniquely determined by a respective position of each foot **150** relative to surface **180** and relative to one another. In such an example, sensor **160** may measure a position and/or rotational orientation of body **110** and/or end effector **120**, which may be compared

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to a target position and/or rotational orientation, and robot controller **170** subsequently may translate one or more feet **150** to bring body **110** and end effector **120** to the target position and/or rotational orientation.

Turning now to FIGS. **2-4**, an illustrative, non-exclusive example of robot **100** is illustrated and indicated at **200**. Where appropriate, the reference numerals from the schematic illustration of FIG. **1** are used to designate corresponding parts of the example of FIGS. **2-4**; however, the example of FIGS. **2-4** is non-exclusive and does not limit robots **100** to the illustrated example of FIGS. **2-4**. That is, robots **100** are not limited to the specific example of FIGS. **2-4**, and robots **100** may incorporate any number of the various aspects, configurations, characteristics, properties, etc. of robots **100** that are illustrated in and discussed with reference to the schematic representation of FIG. **1** as well as variations thereof, without requiring the inclusion of all such aspects, configurations, characteristics, properties, etc. For the purpose of brevity, each previously discussed component, part, portion, aspect, region, etc. or variants thereof may not be discussed, illustrated, and/or labeled again with respect to the example of FIGS. **2-4**; however, it is within the scope of the present disclosure that the previously discussed features, variants, etc. may be utilized with the example of FIGS. **2-4**.

As seen in FIGS. **2-4**, robot **200** is an illustrative, non-exclusive example of a robot **100** that includes a body **110**, three legs **130**, and three feet **150** for moving relative to a surface **180**. As illustrated, body **110** includes a coupling structure **112** that includes a bolt platter into which a plurality of bolts may be inserted to selectively couple end effector **120** to body **110**. Each leg **130** is substantially linear and has a fixed, common length. Each leg **130** includes a body joint **136** in the form of a single-axis hinge and includes a foot joint **138** in the form of a ball-and-socket joint with three rotational degrees of freedom. Each foot **150** includes a planar motor configured to translate foot **150** relative to surface **180** with two degrees of translational freedom.

FIGS. **2-4** additionally illustrate a plurality of locations and rotational orientations that may be assumed by body **110** based on the relative positions of feet **150**. For example, with reference to FIGS. **2-3**, FIG. **3** illustrates a configuration in which body **110** is brought closer to surface **180** relative to the configuration illustrated in FIG. **2** by moving each foot **150** radially outward with respect to a projection of a center point of body **110** onto surface **180**. Additionally, with reference to FIGS. **2** and **4**, FIG. **4** illustrates a configuration in which body **110** is maintained at a generally constant distance above surface **180** relative to the configuration illustrated in FIG. **2**, but in which a rotational orientation of body **110** has been altered by altering the relative positions of feet **150**.

Turning now to FIGS. **5-10**, illustrative, non-exclusive examples of robotic systems **300** are illustrated. A robotic system **300** includes one or more robots **100** and surface **180** such that the robots **100** are positioned for moving along surface **180**. While FIGS. **5-6** illustrate robotic systems **300** utilized in the context of aircraft manufacturing, this is provided as a non-limiting example, and it is within the scope of the present disclosure that robotic systems **300** may be utilized in any appropriate application. In FIG. **5**, robots **100** are schematically represented as triangles; however, this representation is for illustrative purposes only, and is not intended to be indicative of a particular form, size, or appearance of robots **100**.

Robotic system 300 may include a plurality of robots 100. A given robot 100 of the plurality of robots 100 may be configured to perform a distinct task from, and/or may be sized differently from, a different robot 100 of the plurality of robots 100. For example, a given robot 100 may have a corresponding type of end effector 120 operatively coupled to its respective body 110, and a different robot 100 may have a different type of end effector 120 operatively coupled to its respective body 110. Additionally or alternatively, a given robot 100 may have a respective end effector 120 operatively coupled to its respective body 110 between its respective legs 130, while a different robot 100 may have a respective end effector 120 operatively coupled to its respective body 110 opposite its respective legs 130 relative to its body 110.

As further examples, and with reference to FIG. 5, the robots 100 of robotic system 300 may include at least one transporting robot 310 configured to selectively acquire and transport parts 322 to proximate an apparatus 330 being assembled. As used herein, apparatus 330 additionally or alternatively may be referred to as work piece 330, and work piece 330 may include, and/or be, one or more parts 322. Robotic system 300 additionally may include an inventory 320 of parts 322 for assembling apparatus 330, such that surface 180 extends proximate inventory 320 and such that the at least one transporting robot 310 is configured to selectively acquire and transport parts from inventory 320 to proximate apparatus 330.

Additionally or alternatively, the robots 100 of robotic system 300 may include at least one installing robot 312 configured to selectively receive parts 322 from the at least one transporting robot 310 for operatively installing parts 322 on apparatus 330. For example, and with continued reference to FIG. 5, apparatus 330 may include, or be, an aircraft 332 or a portion thereof, and part 322 may be any suitable component of aircraft 332, such as a wing, an engine, or a fuselage component, such that the robots 100 may be configured to support, transport, align, machine, orient, and/or install any suitable part 322. As used herein, part 322 generally may refer to any suitable component that is utilized in assembly of work piece 330 and/or that is included in an assembled work piece 330. Therefore, it is within the scope of the present disclosure that a given component may be referred to both as a part 322 as well as a work piece 330. For example, and as illustrated in FIG. 5, part 322 may take the form of an engine that is installed on a work piece 330 in the form of a wing, and/or part 322 may take the form of a wing that is installed on a work piece 330 in the form of a fuselage.

Surface 180 of robotic system 300 may include one or more travel regions 350 configured for robot 100, such as transporting robot 310, to travel along without being positioned to work on apparatus 330. Additionally or alternatively, Surface 180 of robotic system 300 may include one or more operational regions 360 configured for a robot 100, such as installing robot 312, to be positioned to work on apparatus 330. Travel region 350 may be configured for robot 100, such as transporting robot 310, to travel to and from operational region 360. As illustrated in FIG. 5, travel region 350 may be elongate. For example, travel region 350 may have a width that is not substantially greater than a width of robot 100 traveling along travel region 350 and/or that is substantially less than a dimension of an operational region 360.

As further illustrated in FIG. 5, robotic system 300 additionally may include a system controller 356 configured to selectively translate feet 150 of the robots 100 relative to

surface 180. System controller 356 may be configured to coordinate movement of at least two robots 100 to accomplish a task. For example, system controller 356 may be configured to coordinate a transfer of a work piece from transporting robot 310 to installing robot 312. Additionally or alternatively, system controller 356 may be configured to monitor and coordinate the motion of one or more robots 100 such that robots 100 may accomplish independent tasks without colliding with one another or with their surroundings. System controller 356 may be configured to interface with one or more robots 100 in any suitable manner, such as via a wireless protocol, as schematically represented by lightning bolts in FIG. 5, and/or via a wired communication protocol.

Turning now to FIG. 6, additional illustrative, non-exclusive examples of robotic systems 300 are represented. As illustrated in FIG. 6, surface 180 may assume any appropriate configuration. For example, surface 180 may include one or more horizontal regions 342 and/or one or more vertical regions 344. Additionally or alternatively, surface 180 may include one or more planar regions 346 and/or one or more curved regions 348. As illustrated in FIG. 6, a planar region 346 of surface 180 may include, or be, a horizontal region 342 and/or a vertical region 344, and/or may include a region that is not substantially horizontal or vertical, such as a region that is angled with respect to a horizontal or vertical plane.

As illustrated in FIG. 6, in some examples, robot 100 may be located on surface 180 in a position that is suspended with respect to a ground surface. Stated differently, robot 100 may be positioned on surface 180 such that an attractive force may be necessary to prevent robot 100 from falling off of surface 180. Such an attractive force may be provided by any suitable mechanism, such as a magnetic force between foot 150 and surface 180, a mechanical linkage between foot 150 and surface 180, and/or a vacuum seal between foot 150 and surface 180.

In an example in which foot 150 and/or surface engagement structure 152 includes a planar motor, such as a Sawyer motor, and/or in which foot 150 includes a forcer configured to translate foot 150 relative to surface 180, surface 180 of robotic system 300 may include, or be, a platen configured for use with planar motors. In such an example, a magnetic attraction between foot 150 and surface 180 may facilitate orienting and/or maintaining robot 100 in an elevated position. Additionally or alternatively, and with reference to FIG. 5, a travel region 350 or an operational region 360 of surface 180 may include, or be, a platen configured for use with planar motors.

Additionally or alternatively, and as discussed, surface 180 of robotic system 300 may include one or more air bearings configured to provide a cushion of air between feet 150 of robot 100 and surface 180. In such an example, a selective removal of the cushion of air between feet 150 and surface 180 may provide a vacuum seal that may facilitate orienting and/or maintaining robot 100 in an elevated position.

As further illustrated in FIG. 6, end effector 120 of a robot 100 of robotic system 300 may assume any appropriate orientation with respect to body 110, legs 130, surface 180, and/or apparatus 330. For example, and as discussed, end effector 120 may be positioned opposite legs 130 relative to body 110, such that robot 100 may be substantially entirely between surface 180 and apparatus 330 when robot 100 is manipulating apparatus 330. Alternatively, and as discussed, end effector 120 may be positioned between legs 130, such that apparatus 330 may be positioned substantially between

body **110** of robot **100** and surface **180** when robot **100** is manipulating apparatus **330**. In such a configuration, apparatus **330** may be a free-standing apparatus **330**, such as a wing of aircraft **332**. Additionally or alternatively, and as further illustrated in FIG. **6**, apparatus **330** may be supported by an apparatus supporting structure **334**, such as a table, a scaffold, and/or a conveyor belt.

With reference to the examples of FIGS. **7** and **8**, a robotic system **300** may include one or more conveyors **336** for transporting parts **322**. In such systems **300**, a robot **100** may have an end effector **120** that is configured to be operatively positioned above the conveyors **336**, such as to work on, manipulate, or otherwise engage parts as they travel along the conveyors. In the example of FIG. **7**, the robot **100** is positioned vertically beneath the surface **180** with its end effector **120** opposite its legs **130**. In such a configuration, the robot **100** may easily move its end effector **120** with six degrees of freedom relative to each of two or more conveyors **336**. In the example of FIG. **8**, the robot **100** is positioned vertically above the surface **180** with its end effector **120** operatively coupled to its body **110** opposite its legs **130**. In such a configuration, the robot **100** may easily move its end effector **120** with six degrees of freedom relative to each of two or more conveyors **336**.

Additionally or alternatively, two robots **100** of a plurality of robots **100** of a system **300** may be configured to perform the same, or similar, task, and thus to collectively accomplish a task. As an example, FIG. **9** schematically illustrates two robots **100**, each having an end effector **120** configured to cut a work piece **330**. In the illustrated example, the robots **100** are operatively coupled to the surface **180**, with the surface **180** being positioned vertically above the robots **100** and with the work piece **330** being positioned vertically beneath the robots. Other configurations of robotic systems **300** having two or more robots **100** collectively working together to accomplish a task also are within the scope of the present disclosure.

FIG. **11** schematically provides a flowchart that represents illustrative, non-exclusive examples of methods according to the present disclosure. In FIG. **11**, some steps are illustrated in dashed boxes indicating that such steps may be optional or may correspond to an optional version of a method according to the present disclosure. That said, not all methods according to the present disclosure are required to include the steps illustrated in solid boxes. The methods and steps illustrated in FIG. **11** are not limiting and other methods and steps are within the scope of the present disclosure, including methods having greater than or fewer than the number of steps illustrated, as understood from the discussions herein.

As seen in FIG. **11**, methods **400** of operating a robot **100** includes selectively, independently, and motively translating **410** at least one foot **150** to operatively move a body **110** with six degrees of freedom, and additionally may include working **420** on a work piece **330** with the robot.

Translating **410** may include translating at least one foot **150** and/or all feet **150** of robot **100** with two degrees of translational freedom on a surface **180** and may include translating the at least one foot **150** simultaneously, translating the at least one foot **150** sequentially, and/or a combination thereof. Translating **410** may include translating each foot **150** to a predetermined respective location with respect to at least one other foot **150** and/or the surface **180**, and/or may include translating each foot **150** responsive to information collected by a sensor **160**. Additionally or alternatively, translating **410** may include translating at

least one foot **150** to bring the body **110** to a predetermined location and/or rotational orientation.

Working **420** may include utilizing an end effector **120** to perform an operation on and/or with the work piece **330**. For example, working **420** may include assembling, welding, drilling, cutting, removing material from, placing fiber on, gripping, sensing, and/or lifting the work piece **330**. Working **420** may include performing an operation relating to assembly and/or manufacture, such as aerospace industrial manufacturing.

Translating **410** may include translating the at least one foot to rotate a part **322** relative to a work piece **330** and translate the part toward the work piece. For example, with reference to the example system **300** of FIG. **10**, the translating **410** may result in the part **322** becoming threadingly coupled to the work piece **330**, such as with the work piece **330** having a threaded fastener **338**. As schematically illustrated in FIG. **10**, such a task may be accomplished by coordinating the simultaneous movement of the feet **150** to bring the feet **150** toward each other while also revolving the feet **150** around a point on the surface **180**. As a result, the end effector **120** and the part **322** will rotate and translate away from the surface **180** toward the work piece **330**.

Methods **400** may include operating a single robot **100**, and/or may include operating a robotic system **300** that may include one or more robots **100**. For example, translating **410** may include selectively, independently, and motively translating at least one foot **150** of the one or more robots **100** of the robotic system **300** to operatively move the respective bodies **110** with six degrees of freedom. Similarly, working **420** may include working on the part **322** and/or the work piece **330** with the one or more robots **100**, and may include assembling, welding, drilling, cutting, removing material from, placing fiber on, gripping, sensing, and/or lifting the part **322** and/or the work piece **330** with the one or more robots **100**.

As an illustrative, non-exclusive example, the working **420** may include lifting the part with two or more robots **100** and aligning the part relative to a work piece. In some such examples, the method **400** may further include assembling the part to the work piece. FIG. **5** illustrates an example of a part **322** in the form of a wing and a work piece **330** in the form of a fuselage; however, other examples are within the scope of the present disclosure.

As another illustrative, non-exclusive example, the working **420** may include cutting a work piece, and the translating **410** may include coordinating movement of the two or more robots to collectively cut the work piece, such as discussed herein with reference to FIG. **9**.

Illustrative, non-exclusive examples of inventive subject matter according to the present disclosure are described in the following enumerated paragraphs:

A. A robot for moving relative to a surface, the robot comprising:

a body;

at least two legs, wherein each leg has a proximal end region and a distal end region, and wherein the proximal end region of each leg is operatively coupled to the body at a respective body joint with one rotational degree of freedom; and

at least two feet, wherein each foot is operatively coupled to the distal end region of a respective leg of the at least two legs at a respective foot joint comprising two rotational degrees of freedom, and wherein each foot is configured to be selectively, independently, and motively translated relative to the surface with two degrees of translational freedom.

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A1. The robot of paragraph A, wherein the body is configured to be operatively coupled to an end effector.

A1.1. The robot of paragraph A1, wherein the body is configured to be operatively coupled to the end effector with the end effector positioned between the at least two legs.

A1.2. The robot of any of paragraphs A1-A1.1, wherein the body is configured to be operatively coupled to the end effector with the end effector positioned opposite the at least two legs relative to the body.

A1.3. The robot of any of paragraphs A1-A1.2, further comprising the end effector operatively coupled to the body.

A1.3.1. The robot of paragraph A1.3, wherein the end effector comprises one or more of a welding tool, a drilling tool, a cutting tool, a material removal tool, a fiber placement tool, a gripping tool, a force-torque sensor, a tool changer, and a lifting tool.

A2. The robot of any of paragraphs A-A1.3.1, wherein each body joint defines a single rotational degree of freedom.

A3. The robot of any of paragraphs A-A2, wherein each body joint consists of a revolute joint.

A4. The robot of any of paragraphs A-A3, wherein the body joints are evenly spaced around a periphery of the body.

A5. The robot of any of paragraphs A-A4, wherein each leg of the at least two legs comprises an elongate leg.

A5.1. The robot of paragraph A5, wherein each leg of the at least two legs has the same length.

A6. The robot of any of paragraphs A-A5.1, wherein each leg of the at least two legs has a fixed length.

A7. The robot of any of paragraphs A-A5, wherein each leg of the at least two legs is configured to be selectively increased and decreased in length.

A8. The robot of any of paragraphs A-A7, wherein each leg of the at least two legs is rigid.

A9. The robot of any of paragraphs A-A8, wherein each leg of the at least two legs is at least substantially linear.

A10. The robot of any of paragraphs A-A8, wherein at least one leg of the at least two legs is non-linear.

A11. The robot of any of paragraphs A-A10, wherein the at least two legs comprise three legs, and wherein the at least two feet comprise three feet.

A12. The robot of any of paragraphs A-A10, wherein the at least two legs consist of three legs, and wherein the at least two feet consist of three feet.

A13. The robot of any of paragraphs A-A12, wherein each foot joint defines exactly three rotational degrees of freedom.

A14. The robot of any of paragraphs A-A13, wherein each foot joint comprises one of a spherical joint, a ball joint, a ball-and-socket joint, or a universal joint.

A15. The robot of any of paragraphs A-A14, wherein each foot of the at least two feet comprises a planar motor.

A16. The robot of any of paragraphs A-A15, wherein each foot of the at least two feet comprises one or more wheels, optionally spherical wheels, optionally motorized wheels.

A17. The robot of any of paragraphs A-A16, wherein each foot of the at least two feet comprises one or more air bearings configured to provide a cushion of air between each foot and the surface.

A18. The robot of any of paragraphs A-A17, wherein each foot of the at least two feet is configured to be selectively and releasably fixed to the surface at a respective location.

A19. The robot of any of paragraphs A-A18, wherein each foot of the at least two feet comprises an automated guided vehicle (AGV).

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A20. The robot of any of paragraphs A-A19, further comprising one or more sensors operatively coupled to one or more of the body, the at least two legs, and the at least two feet, wherein the one or more sensors are configured to detect one or more of position in three-dimensional space, orientation in three-dimensional space, and acceleration.

A21. The robot of any of paragraphs A-A20, further comprising a robot controller configured to selectively, independently, and motively translate each foot of the at least two feet relative to the surface.

A21.1. The robot of paragraph A20 when depending from paragraph A20, wherein the robot controller is communicatively coupled to the one or more sensors, and wherein the robot controller is configured to selectively, independently, and motively translate each foot of the at least two feet relative to the surface based at least in part on data received from the one or more sensors.

A22. The use of the robot of any of paragraphs A-A21.1, optionally in a manufacturing environment.

B. A robotic system, comprising:

one or more robots according to any of paragraphs A-A21.1; and

the surface, wherein the one or more robots are positioned for moving along the surface.

B1. The robotic system of paragraph B, wherein the one or more robots comprises two or more robots comprising at least a first robot and a second robot.

B1.1. The robotic system of paragraph B1, wherein the first robot has a first type of end effector operatively coupled to its respective body, wherein the second robot has a second type of end effector operatively coupled to its respective body, and further wherein the first type of end effector is different from the second type of end effector.

B1.2. The robotic system of any of paragraphs B1-B1.1, wherein the second robot is configured to perform a distinct task from the first robot.

B1.3. The robotic system of any of paragraphs B1-B1.2, wherein the second robot is sized differently from the first robot.

B1.4. The robotic system of any of paragraphs B1-B1.3, wherein the first robot has a respective end effector operatively coupled to its respective body between its respective at least two legs, and wherein the second robot has a respective end effector operatively coupled to its respective body opposite its respective at least two legs relative to its respective body.

B1.5. The robotic system of any B1, wherein the first robot and the second robot each have an end effector operatively coupled to its respective body, wherein the end effectors are configured to collectively perform a task, and wherein the first robot and the second robot are positioned relative to each other to work on a work piece to collectively accomplish the task.

B1.5.1. The robotic system of paragraph B1.5, wherein the end effector comprises a cutting tool, and wherein the first robot and the second robot are configured to collectively cut the work piece.

B2. The robotic system of any of paragraphs B-B1.5.1, wherein the one or more robots comprises at least one transporting robot that is configured to selectively acquire and transport parts to proximate an apparatus being assembled.

B2.1. The robotic system of paragraph B2, further comprising an inventory of parts for assembling the apparatus, wherein the surface extends proximate the inventory of parts, and wherein the at least one transporting robot is

configured to selectively acquire and transport parts from the inventory of parts to proximate the apparatus being assembled.

B2.2. The robotic system of any of paragraphs B2-B2.1, wherein the one or more robots further comprises at least one installing robot that is configured to selectively receive parts from the at least one transporting robot for operatively installing parts on the apparatus being assembled.

B3. The robotic system of any of paragraphs B-B2.2, wherein the surface comprises one or more horizontal regions.

B4. The robotic system of any of paragraphs B-B3, wherein the surface comprises one or more vertical regions.

B5. The robotic system of any of paragraphs B-B4, wherein the surface comprises one or more planar regions.

B6. The robotic system of any of paragraphs B-B5, wherein the surface comprises one or more curved regions.

B7. The robotic system of any of paragraphs B-B6, wherein the surface comprises one or more operational regions configured for a robot of the one or more robots to be positioned to work on a work piece.

B8. The robotic system of any of paragraphs B-B7, wherein the surface comprises one or more travel regions configured for a/the robot of the one or more robots to travel along without being positioned to work on a/the work piece.

B8.1. The robotic system of paragraph B8 when depending from paragraph B7, wherein the one or more travel regions are configured for the robot of the one or more robots to travel to and from the one or more operational regions.

B8.2. The robotic system of any of paragraphs B8-B8.1, wherein the one or more travel regions are elongate.

B9. The robotic system of any of paragraphs B-B8.2, further comprising one or more conveyors transporting parts;

wherein the one or more robots comprises a first robot that has an end effector operatively coupled to the body of the first robot, and wherein the end effector is configured to be operatively positioned above the one or more conveyors.

B9.1. The robotic system of paragraph B9, wherein the end effector is operatively coupled to body of the first robot between the at least two legs of the first robot, and wherein at least one of the one or more conveyors extends between the at least two legs of the first robot and beneath the body of the first robot.

B9.1.1. The robotic system of paragraph B9.1, wherein the one or more conveyors comprises two or more conveyors, and wherein the end effector is configured to be operatively positioned above each of the two or more conveyors.

B9.2. The robotic system of paragraph B9, wherein the end effector is operatively coupled to the body of the first robot opposite the at least two legs relative to the body of the first robot, wherein the first robot is positioned vertically beneath the surface, and wherein the one or more conveyors are positioned vertically beneath the first robot.

B9.2.1. The robotic system of paragraph B9.2, wherein the one or more conveyors comprises two or more conveyors, and wherein the end effector is configured to be operatively positioned above each of the two or more conveyors.

B10. The robotic system of any of paragraphs B-B9.2.1, wherein the surface is a platen configured for use with planar motors.

B11. The robotic system of any of paragraphs B-B10, wherein the surface comprises one or more air bearings configured to provide a cushion of air between the feet of the one or more robots and the surface.

B12. The robotic system of any of paragraphs B-B11, further comprising a system controller configured to selectively translate the feet of the one or more robots relative to the surface.

B12.1. The robotic system of paragraph B12, wherein the one or more robots comprises at least two robots, and wherein the system controller is configured to coordinate movement of the at least two robots to accomplish a task.

B13. The use of the robotic system of any of paragraphs B-B13.1, optionally in a manufacturing environment.

C. A method of operating the robot of any of paragraphs A-A21.1, the method comprising:

selectively, independently, and motively translating at least one foot of the at least two feet to operatively move the body with six degrees of freedom.

C1. The method of paragraph C, further comprising: working on a work piece with the robot.

C1.1. The method of paragraph C1, wherein the working comprises one or more of assembling, welding, drilling, cutting, removing material from, placing fiber on, gripping, sensing, and lifting the work piece.

C1.2. The method of any of paragraphs C1-C1.1, wherein the selectively, independently, and motively translating comprises translating the at least one foot to rotate the work piece relative to an object and translate the work piece toward the object.

C1.2.1. The method of paragraph C1.2, wherein the selectively, independently, and motively translating the at least one foot results in the work piece becoming threadingly coupled to the object.

C1.3. The method of any of paragraphs C1-C1.1, wherein the robot comprises an end effector coupled to the body; and

wherein the working comprises operatively positioning the end effector relative to two or more conveyors.

D. A method of operating the robotic system of any of paragraphs B-B12.1, wherein the one or more robots comprises two or more robots, the method comprising:

selectively, independently, and motively translating at least one foot of each of the two or more robots to operatively move the body of each of the two or more robots with six degrees of freedom.

D1. The method of paragraph D, further comprising: working on a work piece with the two or more robots.

D1.1. The method of paragraph D1, wherein the working comprises one or more of assembling, welding, drilling, cutting, removing material from, placing fiber on, gripping, sensing, and lifting the work piece.

D1.2. The method of any of paragraphs D1-D1.1, wherein the work piece is a part utilized in assembly of a second work piece, and wherein the working comprises lifting the part with the two or more robots and aligning the part relative to the second work piece.

D1.2.1. The method of paragraph D1.2, wherein the working further comprises assembling the part to the second work piece.

D1.2.2. The method of any of paragraphs D1.2-D1.2.1, wherein the part is a wing of an aircraft and the second work piece is a fuselage of the aircraft.

D1.3. The method of any of paragraphs D1-D1.1, wherein the working comprises cutting the work piece, and wherein the selectively, independently, and motively translating comprises coordinating movement of the two or more robots to collectively cut the work piece.

As used herein, the terms “adapted” and “configured” mean that the element, component, or other subject matter is designed and/or intended to perform a given function. Thus,

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the use of the terms “adapted” and “configured” should not be construed to mean that a given element, component, or other subject matter is simply “capable of” performing a given function but that the element, component, and/or other subject matter is specifically selected, created, implemented, utilized, programmed, and/or designed for the purpose of performing the function. It is also within the scope of the present disclosure that elements, components, and/or other recited subject matter that is recited as being adapted to perform a particular function may additionally or alternatively be described as being configured to perform that function, and vice versa. Similarly, subject matter that is recited as being configured to perform a particular function may additionally or alternatively be described as being operative to perform that function.

The various disclosed elements of apparatuses, systems, and steps of methods disclosed herein are not required to all apparatuses, systems, and methods according to the present disclosure, and the present disclosure includes all novel and non-obvious combinations and subcombinations of the various elements and steps disclosed herein. Moreover, one or more of the various elements and steps disclosed herein may define independent inventive subject matter that is separate and apart from the whole of a disclosed apparatus, system, or method. Accordingly, such inventive subject matter is not required to be associated with the specific apparatuses, systems, and methods that are expressly disclosed herein, and such inventive subject matter may find utility in apparatuses, systems, and/or methods that are not expressly disclosed herein.

The invention claimed is:

1. A method of operating a robot comprising a body; at least two legs, wherein each leg has a proximal end region and a distal end region, and wherein the proximal end region of each leg is operatively coupled to the body at a respective body joint with one rotational degree of freedom; and at least two feet, wherein each foot is operatively coupled to the distal end region of a respective leg of the at least two legs at a respective foot joint comprising two rotational degrees of freedom, wherein each foot is configured to be selectively, independently, and motively translated relative to a surface with two degrees of translational freedom, and wherein each foot includes a drive means for selectively, independently, and motively translating the foot relative to the surface; the method comprising:

working on a work piece with the robot;

wherein the working on the work piece with the robot includes assembling the work piece with the robot; and wherein the assembling the work piece with the robot includes selectively, independently, and motively translating at least one foot of the at least two feet relative to the surface.

2. The method of claim **1**, wherein the assembling the work piece further includes gripping a part with the robot, and wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes selectively, independently, and motively translating at least one foot of the at least two feet to rotate the part relative to the work piece and translate the part toward the work piece.

3. The method of claim **2**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet results in the part becoming threadingly coupled to the work piece.

4. The method of claim **2**, wherein the robot comprises an end effector operatively coupled to the body, and wherein the gripping the part with the robot includes gripping the part with the end effector.

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5. The method of claim **1**, wherein each foot of the at least two feet comprises a planar motor.

6. The method of claim **1**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes providing a cushion of air between the at least one foot of the at least two feet and the surface.

7. The method of claim **1**, wherein the assembling the work piece further includes selectively fixing at least one foot of the at least two feet to the surface at a respective location.

8. The method of claim **1**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes translating only one foot of the at least two feet.

9. The method of claim **1**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes translating two or more feet of the at least two feet.

10. The method of claim **1**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes translating the at least two feet sequentially.

11. The method of claim **1**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes translating the at least two feet simultaneously.

12. The method of claim **11**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes coordinating the simultaneous movement of the at least two feet to bring the at least two feet toward each other while also revolving the at least two feet around a point on the surface such that the part translates away from the surface and toward the work piece.

13. The method of claim **1**, wherein the robot includes a sensor configured to detect one or more of position in three-dimensional space, orientation in three-dimensional space, and acceleration, and wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes translating each foot of the at least two feet responsive to information collected by the sensor.

14. The method of claim **13**, wherein the sensor is configured to measure a position of the body; wherein the method further comprises comparing the position of the body to a target position; and wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes bringing the body to the target position.

15. The method of claim **13**, wherein the sensor is configured to measure a rotational orientation of the body; wherein the method further comprises comparing the rotational orientation of the body to a target rotational orientation; and wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes bringing the body to the target rotational orientation.

16. The method of claim **1**, wherein the selectively, independently, and motively translating at least one foot of the at least two feet includes monitoring and controlling, with a system controller, motion of the robot to avoid the robot colliding with its surroundings.

17. The method of claim **1**, wherein the assembling the work piece with the robot includes assembling a part to the work piece, wherein the work piece is at least a portion of an aircraft, and wherein the part is a component of the aircraft.

18. A robot, comprising:
a body;

an end effector operatively coupled to the body;
 at least two legs, wherein each leg has a proximal end
 region and a distal end region, and wherein the proxi-
 mal end region of each leg is operatively coupled to the
 body at a respective body joint with one rotational 5
 degree of freedom; and

at least two feet, wherein each foot is operatively coupled
 to the distal end region of a respective leg at a respec-
 tive foot joint comprising two rotational degrees of
 freedom, wherein each foot is configured to be selec- 10
 tively, independently, and motively translated relative
 to a surface with two degrees of translational freedom,
 and wherein each foot includes a drive means for
 selectively, independently, and motively translating the
 foot relative to the surface; 15

wherein the robot is configured to assemble a work piece.

19. A robotic system, comprising:

the robot of claim **18**; and

a system controller configured to selectively translate at
 least one foot of the at least two feet of the robot 20
 relative to the surface to assemble the work piece.

20. The robotic system of claim **19**, wherein the end
 effector is configured to grip a part, and wherein the system
 controller is configured to selectively translate the at least
 one foot of the at least two feet to rotate the part relative to 25
 the work piece and translate the part toward the work piece
 to assemble the part to the work piece.

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